Rb-rich Asymptotic Giant Branch stars in the Magellanic Clouds

D. A. García-Hernández[1], A. Manchado[1,2], D. L. Lambert[3], B. Plez[4], P. García-Lario[5], F. D'Antona[6], M. Lugaro[7], A. I. Karakas[8] and M. A. van Raai[9]

ABSTRACT

We present high-resolution (R∼60,000) optical spectra of a carefully selected sample of heavily obscured and presumably massive O-rich Asymptotic Giant Branch (AGB) stars in the Magellanic Clouds (MCs). We report the discovery of strong Rb I lines at 7800 Å in four Rb-rich LMC stars at luminosities equal to or greater than the standard adopted luminosity limit for AGB stars ($M_{bol}\sim-7.1$), confirming that "Hot Bottom Burning" (HBB) may produce a flux excess in the more massive AGB stars. In the SMC sample, just one of the five stars with $M_{bol}<-7.1$ was detected in Rb; the other stars may be massive red supergiants. The Rb-rich LMC AGB stars might have stellar masses of at least $\sim6-7$ $M_{\odot}$. Our abundance analysis show that these Rb-rich stars are extremely enriched in Rb by up to 10^3-10^5 times solar but seem to have only mild Zr enhancements. The high Rb/Zr ratios, if real, represent a severe problem for the *s*-process, even if the ^{22}Ne source is operational as expected for massive AGB stars; it is not possible to synthesize copious amounts of Rb without also overproducing Zr. The solution to the problem may lie with an incomplete present understanding of the atmospheres of luminous AGB stars.

Subject headings: stars: AGB and post-AGB — stars: abundances — stars: evolution — nuclear reactions, nucleosynthesis, abundances — stars: atmospheres — stars: late-type

1. Introduction

The Magellanic Clouds (hereafter MCs) provide a unique opportunity to study the evolution and nucleosynthesis of low- and intermediate-mass stars ($0.8 < M < 8$ $M_{\odot}$) in low metallicity environments without the uncertainty on distance, and hence luminosity that hinders similar studies in our Galaxy. Low- and intermediate-mass stars experience thermal pulses on the Asymptotic Giant Branch (AGB) and end their lives with a phase of strong mass loss (see e.g., Herwig 2005). The thermal pulses driven by He-burning produce ^{12}C which is mixed to the stellar surface via the "3^{rd} dredge-up" following a pulse. However, in the case of the more massive AGB stars ($M>4$ $M_{\odot}$), the base of the convective envelope is predicted to experience H-burning by Hot Bottom Burning (HBB, e.g., Mazzitelli et al. 1999), so these stars remain O-rich despite the dredge-up. HBB models predict the production of ^{13}C and ^{14}N through the CN cycle as well as ^{7}Li enhancements. Occurrence of HBB in massive AGB stars is supported by previous studies on visually bright MC AGB stars (Plez et al. 1993; Smith et al. 1995). In our own Galaxy, we have recently identified a small group of obscured but infrared-bright stars showing OH maser emission, the OH/IR stars (e.g., Wood et al. 1992), as very

[1]Instituto de Astrofísica de Canarias, C/ Via Láctea s/n, 38200 La Laguna, Spain; agarcia@iac.es

[2]Consejo Superior de Investigaciones Científicas, Spain

[3]W. J. McDonald Observatory. The University of Texas at Austin. 1 University Station, C1400. Austin, TX 78712−0259, USA; dll@astro.as.utexas.edu

[4]GRAAL, Université Montpellier 2, CNRS, Montpellier, France

[5]Herschel Science Centre. European Space Astronomy Centre, Research and Scientific Support Department of ESA. Villafranca del Castillo, P.O. Box 50727. E-28080 Madrid. Spain; Pedro.Garcia-Lario@sciops.esa.int

[6]INAF-Osservatorio Astronomico di Roma

[7]Centre for Stellar and Planetary Astrophysics, Monash University, Clayton 3800, Victoria, Australia

[8]Research School of Astronomy and Astrophysics, Mt Stromlo Observatory, Weston Creek ACT 2611, Australia

[9]Sterrenkundig Instituut, University of Utrecht, Postbus 80000, 3508 TA Utrecht, The Netherlands

massive (4−8 $M_\odot$) O-rich AGB stars experiencing HBB, as indicated by their strong Li overabundances (García-Hernández et al. 2007).

Theoretical models predict also the presence of *s*-process elements such as Rb, Zr, Sr, etc. at the stellar surface as a consequence of the "3^{rd} dredge-up" episodes (Busso et al. 1999). According to recent understanding, $^{13}C(\alpha,n)^{16}O$ is the preferred neutron source in the He-shell for masses around 1−4 $M_\odot$, while for more massive stars neutrons are mainly released by $^{22}Ne(\alpha,n)^{25}Mg$. This is because activation of ^{22}Ne requires the higher temperatures ($T > 3 \times 10^8$ K) reached during thermal pulses in more massive AGB stars (Lugaro & van Raai 2008). The relative abundance of Rb to other nearby s-elements such as Zr (i.e., the Rb/Zr ratio) is sensitive to the neutron density owing to branchings in the s-process path at ^{85}Kr and ^{86}Rb (Lambert et al. 1995; Abia et al. 2001; van Raai et al. 2008). Since the ^{22}Ne neutron source produces much higher neutron densities than the ^{13}C neutron source, the Rb/Zr ratio is a discriminant of the operation of the ^{13}C versus the ^{22}Ne neutron source and, as such, a good indicator of the progenitor stellar mass in AGB stars.

Interestingly, we discovered strong Rb overabundances (up to 10−100 times solar) with apparently only mild Zr enhancements in massive galactic O-rich AGB stars (García-Hernández et al. 2006, 2007). This work provided the first observational suggestion that ^{22}Ne is the dominant neutron source in (presumably) massive AGB stars. Rb was not found to be overabundant in the few unobscured O-rich massive AGBs previously studied in the SMC (Plez et al. 1993). With our strategy that was successful in finding massive AGB stars in the Galaxy, we extended optical spectroscopy to obscured and presumably massive MC O-rich AGB stars. Here, we report for the first detections of massive Rb-rich AGB stars in the MCs.

2. Optical observations

A sample of 24 obscured O-rich AGBs in the MCs was carefully selected from the literature. Most of the known MC OH/IR stars (Wood et al. 1992; Marshall et al. 2004 and references therein) were included in our sample, as they are, in principle, the most massive and extreme AGBs known in the Clouds.

Our spectroscopic observations were carried out during 2007 October 27−29 at the ESO-VLT (Paranal, Chile) with the high-resolution spectrograph UVES (Dekker et al. 2000). We used the 0.7" slit (R∼60,000) in the Red Arm Mode (∼5,700−9,600 Å), which gives a resolution of ∼0.13 at 7800 Å (the Rb I line). The exposure times varied between 30 minutes for the less obscured stars and 3 hours for the Rb-detected stars. The goal was to achieve a final S/N ratio of ≥30−50 at 7800 Å. All 24 obscured O-rich AGB candidates (17 in the LMC and 7 in the SMC) were inspected at the telescope but useful spectra were obtained for only 10. The other 14 sources were either too faint at 7800 Å or the optical counterpart was not found. In addition, we observed 10 (4 in the LMC and 6 in the SMC) very luminous and less obscured stars with previous Li information. For comparison purposes, we also obtained a spectrum for IRAS 04553−6825, a well known LMC massive red supergiant. Table 1 presents relevant information for the sample stars with useful spectra: the obscured and unobscured O-rich AGBs as well as the massive red supergiant (RSG) stars.

The spectra were reduced at the telescope using the UVES data reduction pipeline (Ballester et al. 2000). Fig. 1 shows sample spectra around the 7800 Å Rb I line. In general, all stars show extremely red spectra[1], severely dominated by strong molecular bands of TiO and sometimes ZrO. Remarkably, the Rb-detected stars seem to be spectroscopically different from the non Rb-detected stars (see Table 1) in some spectral regions such as ∼7400−7600, 7925−7975, 8100−8150, and 9250−9350 Å[2]. The latter regions are dominated by numerous and as yet unidentified molecular features. In addition, the Rb I absorption lines may have blue-shifted circumstellar absorption components. Unfortunately, the accompanying circumstellar Rb I emission component sometimes coincides with the photospheric Rb I absorption. Thus, in some cases, the circum-

[1] Note that the Rb-detected stars display the reddest spectra with the flux level falling dramatically at wavelengths shorter than 7000 Å.

[2] The non Rb-detected LMC stars RGC 69 and SHV G149006 display spectra identical to the Rb-detected ones and we identify them as very massive AGBs.

stellar emission masks the photospheric absorption and this prevents us measuring a reliable Rb abundance in these stars.

3. Abundance analysis

Our abundance analysis combines state-of-the-art line-blanketed model atmospheres for cool stars and extensive linelists. Basically, we have followed the procedure that we used for the galactic O-rich AGB stars (see García-Hernández et al. 2006, 2007 for more details). The principal difference is that we have constructed a grid of MARCS model atmospheres (Gustafsson et al. 2008) at the metallicity of the MCs (we assumed z=[M/H]=−0.3 and −0.7 for the LMC and SMC, respectively). Then, we generated a grid of MARCS synthetic spectra with effective temperatures in the range T_{eff}=2600−4000 K in steps of 100 K, the FWHM in the range 200−600 mÅ in steps of 50 mÅ (this step accounts for the instrumental profile and the macroturbulence), and keeping all the other stellar parameters fixed: surface gravity *logg*=0.0, microturbulence ξ=3 km s^{-1}, stellar mass M=1 $M_\odot$[3], and scaled solar abundances.

The observed spectra were compared to the synthetic ones in the region 7775−7835 Å that covers the Rb I line at 7800 Å; see Fig. 2. We first determined which of the spectra from our grid of models provides the best fit to the TiO bandheads and the pseudocontinuum around the Rb I line by adjusting mainly the T_{eff}. Then, the rubidium content[4] was estimated by fitting the Rb I line. When an acceptable S/N ratio (>30) was achieved around 7000 Å, the T_{eff} was checked from syntheses of the region 7025−7075 Å which includes the TiO red-degraded bandhead at 7054 Å. We found a typical difference of ±100 K between the temperatures. In addition, we derived the Zr abundance or an upper limit from synthesis of the 7440 Å Zr I line or the ZrO molecular bands in the intervals 6455−6499 and 6900−6950 Å(see below).

A surprising result immediately appeared: the Rb abundances obtained for the stars not having a strong 7800 Å Rb I line were unrealistically low ([Rb/Fe]≤−1.7 in some LMC stars and similar limits for SMC stars) given the anticipated initial Rb abundances for MC stars. It is to be noted that the metallicity derived from the 7798 Å Ni I and 7808 Å Fe I lines close to the Rb I line is significantly lower (by up to 1 dex!) than the one derived from metallic lines (e.g., the Fe I lines at 7443 and 7446 Å) around the 7440 Å Zr I line. For example, in the LMC Li-rich Rb-low AGB star HV 5584, [Fe/H]=−1.5 and [Fe/H]=−0.4 are obtained from the 7800 Å and 7440 Å regions, respectively. The disparity in the Fe abundances is likely attributable to a missing opacity in the real atmosphere and to deficiencies in the adopted TiO line list (see also Lambert et al. 1995; Abia et al. 2001). The TiO line list plays a much greater role at 7800 Å than at 7440 Å. Therefore, we computed the [Rb/z] and [Zr/z] ratios using the metallicity derived from the metallic lines (calibrated against the spectrum of Arcturus) close to the 7800 Å Rb I and 7440 Å Zr I lines, respectively. However, the analysis of the Rb-detected stars is an even trickier business. The available line list for the 7440 Å region is incomplete for these stars, probably the list is missing lines linked to the yet unidentified molecule responsible for several bandheads in this region, bandheads not present in the Rb-weak and less luminous stars. Thus, we are presently forced to use the ZrO bands to set the Zr abundance in the Rb-detected stars. At least in the less luminous MC AGB stars such as HV 5584, HV 1645 or HV 11427, the Zr abundance from the 7440 Å Zr I line is in very good agreement (±0.1 dex) with that derived from the ZrO bands.

The spectroscopic effective temperatures and abundances are summarised in Table 1. The uncertainties[5] of the derived abundances are estimated to be 0.8 and 0.5 dex for Rb and Zr abundances, respectively. The final fit to the 7800 Å region of the LMC Rb-rich star IRAS 04498-6842 is shown in Fig. 2.

[3] The output synthetic spectra are not sensitive to the mass of the star in the range 1−10 $M_\odot$ (García-Hernández et al. 2007).

[4] The Rb isotopic and hyperfine structure was considered, for which we assumed a solar Rb isotopic composition (García-Hernández et al. 2006).

[5] These errors reflect mostly the sensitivity of the derived abundances to changes in the atmospheric parameters taken for the modelling.

4. The low Rb stars

Setting aside the few Rb-rich stars, non-detection of the 7800 Å Rb I line corresponds to a limit [Rb/z]≤ -0.5 for both AGB and RSG stars. Obviously, it is of interest to compare this limit with the value for warmer giants less evolved than AGB and RSG stars and with simpler spectra. Unfortunately, Rb abundances have not yet been reported for such stars, but Y and Zr abundances are available. Pompéia et al. (2008) find [Y/Fe] $\simeq -0.3$ and [Zr/Fe] ~ -0.5 for LMC red giants. The limit [Rb/z]≤ -0.5 is consistent with these values. The AGB stars appear to show a mild Zr excess over [Zr/Fe] ~ -0.5. A mild Rb excess can not yet be ruled out given the uncertainty affecting the Rb abundance and the possibility that non-LTE effects have resulted in an underestimate of the Rb abundance (Plez et al. 1993). In short, the low Rb stars with a mild Zr excess appear to be AGB stars that have experienced thermal pulses.

5. The Rb-rich AGBs

The main result of our survey is that we have discovered strong Rb I lines in AGB stars (4 stars in the LMC and 1 in the SMC) in a low-metallicity extragalactic system. As in our Galaxy, the Rb-strong stars in the MCs belong to the class of OH/IR stars (Table 1). Unfortunately, we could estimate photospheric Rb abundances in only three LMC Rb-rich stars due to the clear presence of blue-shifted circumstellar Rb I lines in the other Rb-detected stars (Table 1). The extremely high Rb abundances observed (up to 10^3-10^5 times solar) among the LMC stars are remarkable. These Rb abundances at their maximum are a factor of ten or more greater than displayed by their Galactic counterparts. Note that, when the S/N ratio is high enough at 6708 Å, as is the case for two of the four LMC Rb-rich stars, the Li I 6708 Å feature seems to be strong indicating Li-production by a HBB AGB star. The Li feature is also strong for other AGB stars in both the LMC and SMC that are not Rb-rich; an indicator that Li synthesis and Rb synthesis are not tightly coupled.

The well known period-luminosity relation for luminous AGB stars (Mira variables) shows that the Rb-rich stars are those with the longest periods. In addition, a common mark of the Rb-rich stars that sets them apart from other AGB stars is their bolometric luminosity – see Fig. 3 for a plot of M_{bol} vs. [Rb/z]. References to M_{bol} estimates are given in Table 1. Bolometric magnitude estimates are accurate to about 0.5 magnitudes (Whitelock et al. 2003). The Rb-rich stars in the LMC are brighter ($-8<M_{bol}<-7$) than the Rb-poor stars. Fig. 3 includes the Li-rich HBB-AGBs previously studied in the SMC (Plez et al. 1993). Unfortunately, we do not have a star in common with Plez et al. (1993), but our Rb and Zr abundances for the SMC HBB-AGBs agree very well (within the errors) with their reported abundances. Note, however, that Plez et al. derived the metallicity from the metallic lines in the 7400−7600 Å window which is only slightly blanketed by TiO molecular lines. The use of the metallic lines near to the Rb I line will probably bring up their reported Rb abundances even closer to our values.

The apparent onset of Rb-rich stars at luminosities of M_{bol} of -7.1 is intriguing. This bolometric luminosity is the generally adopted limit for AGB stars (Paczyński 1971). Stars more luminous than this limit have been thought to be massive red supergiants[6] although presence of AGB stars at luminosities brighter than the standard limit - as our observations confirm - can be due to a luminosity contribution from HBB in a massive AGB star. Models suggest that the Li-rich HBB-AGBs with $-7<M_{bol}<-6$ in the LMC are the descendants of stars with initial masses M $\sim 4-4.5$ $M_\odot$ (Ventura et al. 2000): our Rb-rich LMC AGB stars with $M_{bol} < -7$ might have initial stellar masses of at least $\sim$6−7 $M_\odot$.

6. A Rubidium problem

The Rb problem posed by the four LMC stars has two parts: the high Rb abundance and the extraordinary [Rb/Zr] ratio (i.e., the apparent lack of a Zr enrichment). Our discovery of the class of Rb-rich LMC AGB stars is assured by visual inspection of our spectra (Fig. 1). The severity of the Rb overabundance ([Rb/z]$\sim +2.8$ to $+5.0$) may be somewhat uncertain because the Rb I line is strong and saturated with possible circumstellar

[6]Examples in our sample of massive red supergiants are noted in Table 1. Absence of Li (also Rb and Zr) is a mark of a RSG (e.g., IRAS 04553-6825)

contamination. Note that all Rb-detected stars also display strong Rb I lines at 7947 Å, confirming the high Rb abundance from the 7800 Å line. For example, [Rb/z]=+5.0 and +3.3 are obtained from the 7947 Å Rb I line for the Rb-rich AGBs IRAS 04498−6842 and IRAS 04407−7000, respectively. The upper limit to the Zr abundance that gives ratios [Rb/Zr] of 3 to 4 (Table 1) comes from a fit to ZrO bands.

A Rb overabundance is naturally attributed to the *s*-process and most probably to its operation in massive AGB stars with the higher neutron density from the ^{22}Ne source taking the *s*-process path through the ^{85}Kr branch to ^{87}Rb and resulting in an increase in Rb abundance relative to the low neutron density path to ^{85}Rb (García-Hernández et al. 2006). Although the increase in the Rb abundance between low and high neutron density *s*-process paths is about an order of magnitude, the predicted Rb/Zr and Rb/Y ratios do not assume extreme values. Present massive AGB nucleosynthesis models can qualitatively describe the observations of Rb-rich AGBs in the sense that increasing Rb overabundances with increasing stellar mass and with decreasing metallicity are theoretically predicted (van Raai et al. 2008, 2009). However, these theoretical models are far from matching the extremely high Rb enhancements that we observe. Predictions for massive AGB models at the LMC and SMC metallicities (and solar for comparison) computed for the ^{22}Ne source with the Monash stellar nucleosynthesis code based on the Mt. Stromlo stellar structure code (e.g., Karakas & Lattanzio 2007) are shown in Table 2. If the "3^{rd} dredge-up" efficiency remains as high as before the onset of the superwind phase during the final few pulses of a massive AGB star, then [Rb/Fe] increases as well as [Zr/Fe] (e.g., up to +1.3 and +0.8, respectively, in the M=6 $M_{\odot}$, LMC case). Even considering higher AGB masses, within the framework of the s-process it is not possible to produce extremely high Rb abundances without co-producing Zr at similar levels because both Rb and Zr belong to the first s-process peak.

The extraordinary [Rb/Zr] values are likely artefacts of the analysis and possibly a result of the necessity of using the ZrO bands to set the Zr abundance. Non-LTE effects and a failure of the adopted models to represent the real stars are surely contributing factors too. If the large [Rb/Zr] values are real, we can offer no explanation in terms of nucleosynthesis. Additional observations of luminous AGB stars are needed to confirm that Rb-rich stars are confined to bolometric magnitudes $M_{bol} = -7.1$ and brighter, and that the SMC also contains similar stars to the four LMC examples. Despite the uncertainties in the Rb abundance determinations, the occurrence of Rb-rich stars among the most luminous AGB stars – HBB stars as indicated by the presence of Li – in the LMC is assured.

This work is based on observations made at ESO, 080.D-0508(A). We are very grateful to R. Gallino and L. Siess for helpful discussions. DLL wishes to thank the Robert A. Welch Foundation of Houston, Texas for support through grant F-634.

Facilities: VLT:Kueyen (UVES).

REFERENCES

Abia, C., Busso, M., Gallino, R. et al. 2001, ApJ, 559, 1117

Ballester, P., Modigliani, A., Boitiquin, O. et al. 2000, ESO Messenger 101, 31

Busso, M., Gallino, R., & Wasserburg, G. J. 1999, ARA&A, 37, 239

Dekker, H., D'Odorico, S., Kaufer, A. et al. 2000 *in Optical and IR Telescopes Instrumentation and Detectors*, eds I. Masanori & A. F. Morwood Proc. SPIE 4008, 534

Elias, J. H., Frogel, J. A., & Humphreys, R. M. 1980, ApJ, 242, L13

Elias, J. H., Frogel, J. A., & Humphreys, R. M. 1985, ApJS, 57, 91

García-Hernández D. A., García-Lario P., Plez, B. et al. 2006, Science, 314, 1751

García-Hernández D. A., García-Lario P., Plez, B. et al. 2007, A&A, 462, 711

Gustafsson, B., Edvardsson, B., Eriksson, K. et al. 2008, A&A, 486, 951

Herwig, F. 2005, ARA&A, 43, 435

Hughes, S. M. G., & Wood, P. R. 1990, AJ, 99, 784

Karakas, A. I., & Lattanzio, J. C. 2007, PASA, 24, 103

Lambert, D. L., Smith, V. V., Busso, M. et al. 1995, ApJ, 450, 302

Lugaro, M., & van Raai, M. 2008, JPhG, 35, 014007

Mazzitelli, I., D'Antona F., Ventura P., 1999, A&A, 348, 846

Marshall, J. R., van Loon, J. Th., Matsuura, M. et al. 2004, MNRAS, 355, 1348

Paczyński, B. 1971, Acta Astr., 21, 417

Plez, B., Smith, V.V., & Lambert, D.L. 1993, ApJ, 418, 812

Pompéia, L., Hill, V., Spite, M. et al. 2008, A&A, 480, 379

Reid, N., Glass, I. S., & Catchpole, R. M. 1988, MNRAS, 232, 53

Smith, V.V., Plez, B., & Lambert, D.L. 1995, ApJ, 441, 735

van Raai, M. A., Lugaro, M., Karakas, A. I. et al. 2008, in AIP Conf. Ser. 1001, Evolution and Nucleosynthesis in AGB Stars (New York: AIP), 146

van Raai, M. A., Lugaro, M., Karakas, A. I. et al. 2009, in "The 10th Symposium on Nuclei in the Cosmos" (in press)

Ventura, P., D'Antona F., & Mazzitelli, I. 2000, A&A, 363, 605

Whitelock, P., Feast, M., Menzies, J., et al. 1989, MNRAS, 238, 769

Whitelock, P., Feast, M., van Loon, J. Th., et al. 2003, MNRAS, 342 86

Wood, P. R., Bessel, M. S., & Fox, M. W. 1983, ApJ, 272, 99

Wood, P. R., Whiteoak, J. B., Hughes, S. M. G., et al. 1992, ApJ, 397, 552

This 2-column preprint was prepared with the AAS LaTeX macros v5.2.

Table 1

The MC O-rich AGB sample: spectroscopic temperatures and abundances[a]

Name	T_{eff}	[Rb/z][b]	[Zr/z][c]	Li I[d]	M_{bol}	Period	Ref[e].	Type[f]
				LMC				
IRAS 04498−6842	3400	+5.0	$\leq$+0.3*	yes	−7.72	1292	1	OH/IR
IRAS 04407−7000	3000	+3.2	...	...	−7.11	1199	1	OH/IR
IRAS 04516−6902	3000	+3.2*	$\leq$+0.3*	yes	−7.11	1091	1	OH/IR?
IRAS 05558−7000	3400	+2.8	...	...	−6.97	1220	1	OH/IR
IRAS 05298−6957	4000	$\leq$−0.3*	+0.0	no	−6.72	1280	1	OH/IR
IRAS 05329−6708	3900	−0.5	+0.5	no	−6.95	1262	1	OH/IR
IRAS 04553−6825	3400	$\leq$−0.5	−0.5*	no	−9.19	841	1	RSG
RGC 15	3400	+0.1	$\leq$−0.2*	no	−6.53	760	2	non HBB-AGB
HV 5584	3500	$\leq$−0.5	+0.1	yes	−6.27	500	3	HBB-AGB
RGC 69	3300	$\leq$−0.5	−0.2*	yes	−6.49	648	2	HBB-AGB
SHV G149006	3100	$\leq$−0.7	−0.2*	yes	−6.65	636	4	HBB-AGB
				SMC				
IRAS 00483−7347	3400	+1.7*	...	...	−7.20	1200	5	OH/IR?
IRAS 00591−7307	3400	$\leq$−1.0	−0.2	no	−8.30	$\geq$1000	6	RSG/AGB?
IRAS 01082−7335	3300	$\leq$−1.0	$\leq$+0.2*	no	...	...	...	RSG
MSX SMC 168	3700	−1.0	−0.1	no	...	...	...	RSG
HV 838	3400	$\leq$−0.5	+0.2	yes	−7.18	663	3	HBB-AGB
HV 1645	3400	$\leq$−0.5	−0.4	yes	−4.68	300	3	HBB-AGB
HV 1719	3400	+0.4*	+0.7*	yes	−6.68	531	3	HBB-AGB
HV 11427	3500	$\leq$−0.5	+0.0	no	−5.04	251	3	non HBB-AGB
NGC371 R20	3900	−0.5	−0.2	no	−8.36	580	3	RSG
NGC371 29	3400	$\leq$+0.0	−0.3	no	−7.36	530	3	RSG/AGB?

[a]Relative to the solar photospheric values: logε(Rb, Zr)=2.6.

[b]For $T_{eff} \geq 3300$ K, z is the average of the Fe and Ni abundances estimated from the closest Fe I and Ni I lines, while for $T_{eff} < 3300$, z=[M/H]=−0.3 and −0.7 are assumed for the LMC and SMC, respectively. The asterisk means that the Rb I line has a circumstellar origin and the given value corresponds to the photospheric abundance needed to fit the depth of the observed circumstellar line. These abundances must be considered with caution but they usually represent a rough estimation of the photospheric Rb content.

[c]Zr abundances from the 7440 Å Zr I line where z is the Fe abundance estimated from the closest Fe I lines. The asterisk means that the Zr abundance is estimated from the ZrO molecular bands where, because of the lack of useful metallic lines, z=[M/H]=−0.3 and −0.7 are assumed for the LMC and SMC, respectively. Note that no entry means that the S/N is too low for Zr abundance determinations.

[d]No entry means that the S/N is too low to infer the presence of Li I at 6708 Å. The detection or non-detection of Li generally gives a lower and upper limit of logε(Li)=12+logN(Li)>1.0 and <0.0, respectively.

[e]References for bolometric magnitude and period of variability.

[f]OH/IR is assigned to very luminous stars ($M_{bol} \leq -6.7$) showing OH maser emission, extremely long periods (> 1000 days) and large amplitude of variability (ΔK>1.2 mag), being very obscured (J−K$\geq$3) and very bright in the mid-infrared ($F_{25} \geq$1 Jy, when detected by the IRAS satellite). In contrast, massive Red Supergiant (RSG) stars are even more luminous than OH/IRs and they are characterized by a small amplitude of variability (ΔK<0.5 mag). HBB-AGBs were previously known to be Li-rich (Smith et al. 1995) and they generally are less luminous and obscured than OH/IRs and they are characterized by periods shorter than 700 days.

References. — (1) Whitelock et al. (2003); (2) Reid, Glass & Catchpole (1988); (3) Wood, Bessel & Fox (1983); (4) Hughes & Wood (1990); (5) Whitelock et al. (1989); (6) Elias, Frogel and Humphreys (1980,1985).

Table 2

Predictions for massive AGB models.

Mass	z	[Zr/Fe]	[Rb/Fe]
5 $M_\odot$	solar	+0.01	+0.05
6 $M_\odot$	solar	+0.07	+0.21
5 $M_\odot$	LMC	+0.21	+0.56
6 $M_\odot$	LMC	+0.41	+0.79
5 $M_\odot$	SMC	+1.07	+1.11

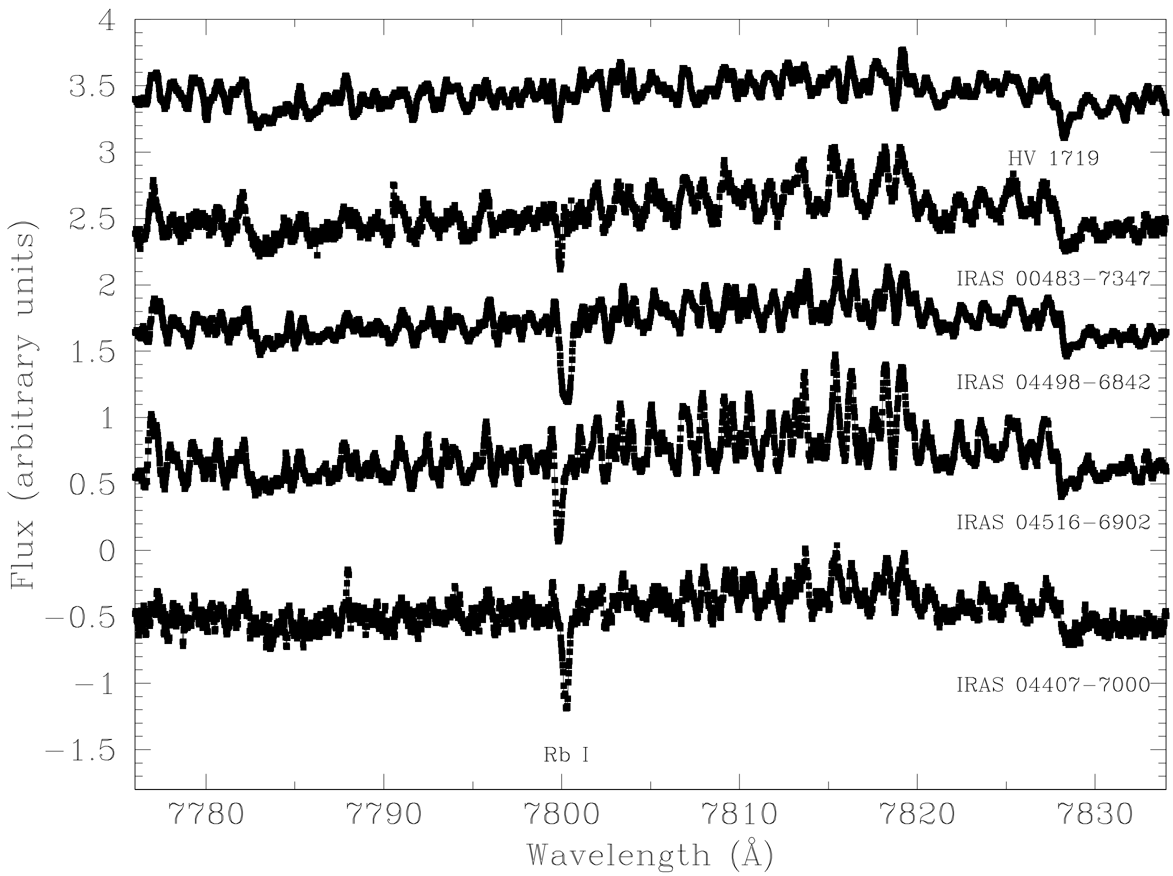

Fig. 1.— Sample spectra around the 7800Å Rb I line. The lower three stars (IRAS 00498-6842, 04516-6902, and 04407-7000) are Rb-rich LMC stars. The upper two stars (HV 1719 and IRAS 00483-7347) with a much weaker Rb I line are from the SMC.

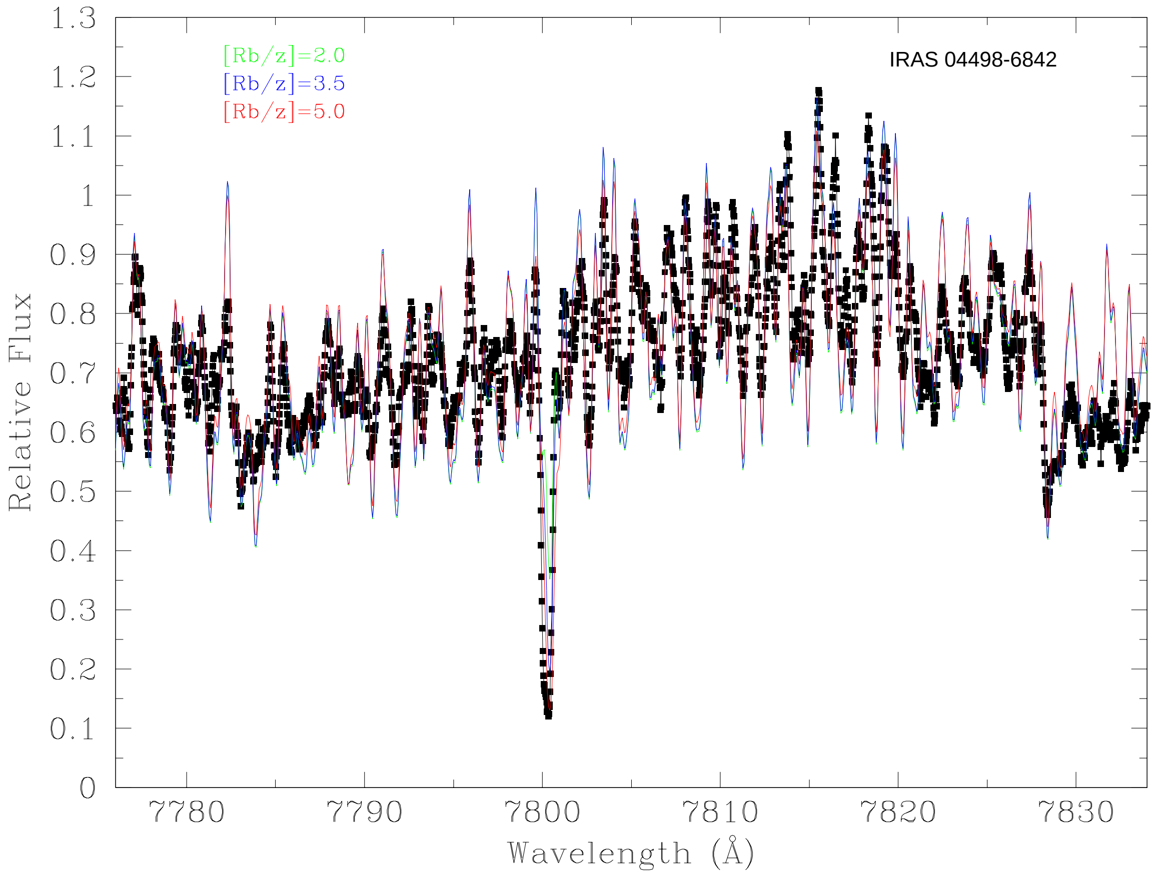

Fig. 2.— Fit of the best synthetic spectrum (red) to the observed spectrum (black) around the 7800Å Rb I line for the Rb-rich LMC star IRAS 04498−6842. The synthetic spectra obtained for [Rb/z]=+2.0 (green) and [Rb/z]=+3.5 (blue) are also shown.

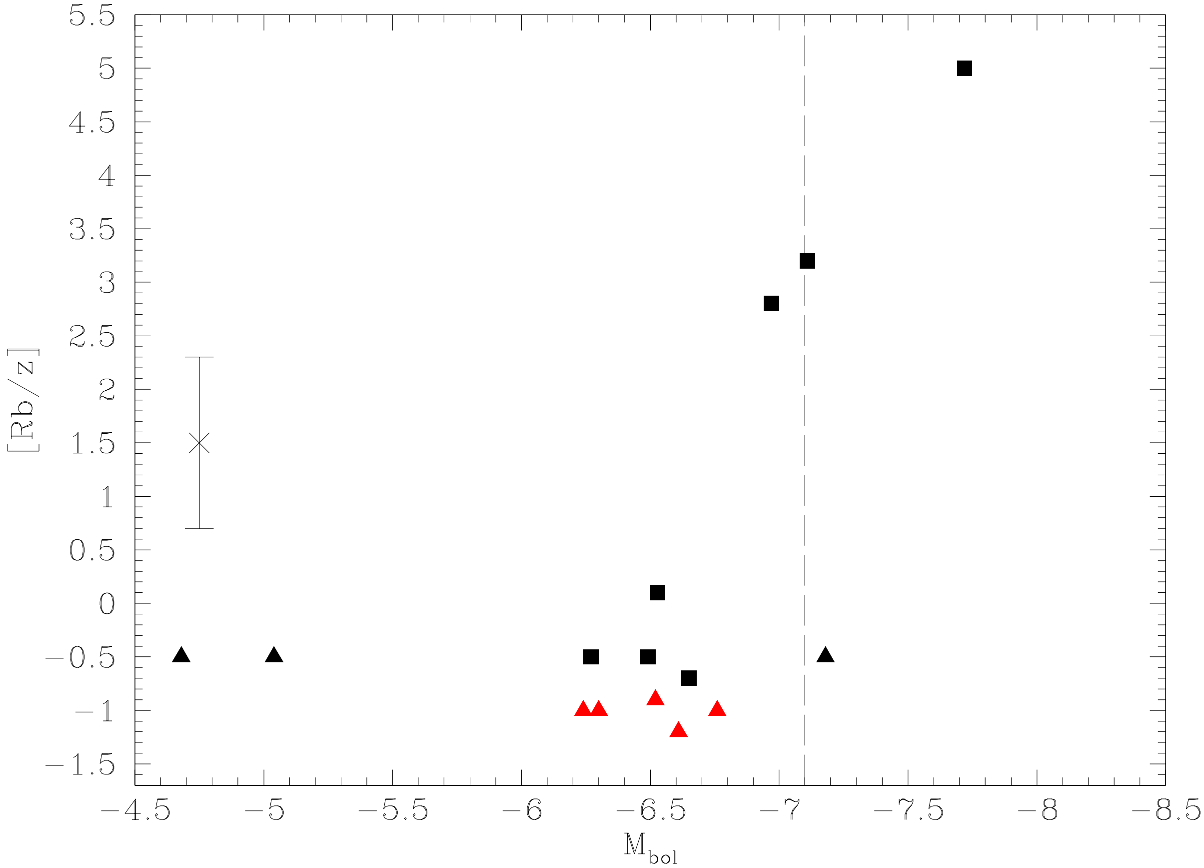

Fig. 3.— Observed Rb abundances (squares and triangles for the LMC and SMC, respectively) versus M_{bol}. Red triangles correspond to the visually bright HBB-AGB SMC stars previously studied by Plez et al. (1993). A typical error bar of ±0.8 dex is shown. The dashed vertical line marks the theoretical luminosity limit (M_{bol}=−7.1; Paczyński 1971) for AGB stars.